5

METHOD AND APPARATUS FOR CORRECTING DIGITAL IMAGES

10 INVENTORS
Robert W. Turner
Pauline Joe
Mark A. Zenor

FIELD OF THE INVENTION

15   This invention relates generally to digital cameras and, more particularly, to electro-optic framing cameras.

RELATED APPLICATIONS

This application is related to concurrently-filed U.S. Patent Application Ser. No. _____, atty. docket number BOEI-1-1180; and U.S. Patent Application Ser. No.

20   _____, atty. docket number BOEI-1-1181, all filed _____ and all hereby incorporated by reference.

BACKGROUND OF THE INVENTION

Homeland defense, environmental base-lining, emergency responses to natural and manmade disasters, agricultural analysis, and other change detection applications need an

25   ability to acquire real-time, high-resolution spatial and multispectral imagery to support situational evaluation of an environment. In order to effectively and efficiently support situational evaluation, multispectral image generation must be accurate and attainable at a minimum cost. For homeland security and environmental monitoring, low cost multispectral sensors can be used to generate digital multispectral images. However, digital images

30   generated by multispectral sensors, such as electro-optic framing cameras, may contain

image streaking caused by electronic noise of the sensor. The streaking results in a decrease in the radiometric accuracy of images. Therefore, removal of streaking effects is important for producing more radiometrically accurate images.

Multispectral sensors or digital cameras with electronic shutters, such as a Phillips
5   liquid crystal device or other cameras with frame store devices, cause light scattering that also reduces the radiometric accuracy of an image.

Therefore, there exists an unmet need to produce low-cost, radiometrically accurate images.

SUMMARY OF THE INVENTION

10   The present invention provides methods, systems, and computer-based program products for correcting image streaking, light scattering, and other effects in digital images generated by multispectral sensors.

According to exemplary embodiments of the present invention, an image frame (i.e., the image frame is what a user desires to view), a plurality of image frames from the digital
15   sensor when exposed to dark, i.e. light below a predefined luminance level, and a plurality of image frames from the digital sensor when exposed to light above a predefined luminance level are received. The received image frame is corrected based on the received plurality of image frames exposed to dark and the plurality of image frames exposed to light.

In accordance with further aspects of the invention, each image frame includes a
20   plurality of frame units. A mean value for each frame unit of the plurality of image frames exposed to dark and a mean value for each frame unit of the plurality of image frames exposed to light are calculated. A first image frame is generated by subtracting the calculated mean value for each frame unit of the plurality of image frames exposed to dark from the corresponding frame unit in the received image frame. A second image frame is generated by
25   subtracting the calculated mean value for each frame unit of the plurality of image frames exposed to dark from the calculated mean value for each corresponding frame unit of the plurality of image frames exposed to light. A third image frame is generated by dividing each frame unit in the first image frame from the corresponding frame unit in the second image frame. An average of frame units is calculated within a predefined center section of the
30   second image frame. A fourth image frame is generated by multiplying each frame unit in the third image frame by the calculated average of the center section frame units, thereby producing a corrected image frame of the received image frame.

In accordance with other aspects of the present invention, all the received image frames are enhanced based on characteristics of the digital sensor. Enhancing a region of
35   interest is determined based on evaluating a masked region of the digital sensor, which

- 2 -

BLACK LOWE & GRAHAM ᴾᴸᴸᶜ

816 Second Avenue
Seattle, Washington 98104
206.381.3300 • F: 206.381.3301

prevents light from reaching the sensor detectors. A standard deviation of the frame units is determined for a determined region of interest within the masked region. A threshold value is determined based on the determined standard deviation. A mean of the frame units in the determined region of interest that are below the determined threshold value is determined.

5   Enhanced image frames are generated based on the determined mean of the frame units and a coefficient.

In accordance with still further aspects of the present invention, light scattering effects are removed from the corrected image frame based upon characteristics of the digital sensor. The characteristics of the digital sensor include light scattering effects of each frame

10   unit upon each frame unit. Light scattering effects are based upon distance between the respective frame units.

BRIEF DESCRIPTION OF THE DRAWINGS

The preferred and alternative embodiments of the present invention are described in detail below with reference to the following drawings.

15   FIGURE 1 is a block diagram of an exemplary system formed in accordance with the present invention;

FIGURES 2-5, and 8 are flow diagrams of an exemplary process performed by the system shown in FIGURE 1;

FIGURE 6 illustrates aspects of the process shown in FIGURE 4;

20   FIGURE 7 illustrates image graphics as it relates to a portion of the process of FIGURE 6; and

FIGURE 9 is a graphical example of some of the processing performed in the process of FIGURE 8.

DETAILED DESCRIPTION OF THE INVENTION

25   The present invention provides methods, systems, and computer-based products for correcting image streaking, light scattering, and other effects in digital images generated by multispectral sensors.

FIGURE 1 illustrates an exemplary system 40 for producing radiometrically accurate images. The system 40 includes a sensor 44, a processor 46, memory 48, a display 50, and a

30   user interface 52. The processor 46 is suitably coupled to the sensor 44, the memory 48, the display 50, and the user interface 52. Non-limiting examples of the sensor 44 are multispectral sensors, digital cameras, electro-optic framing cameras, and cameras that include frame store devices (i.e., charge coupled device (CCD)), such as that produced by Phillips. The sensor 44 includes an optical element 54, such as an electronic shutter, that

35   causes light scattering. The sensor 44 is typically used in aircraft to take pictures of the

- 3 -

BOEI-1-1182AP.doc

25315

PATENT TRADEMARK OFFICE

BLACK LOWE & GRAHAM PLLC

816 Second Avenue
Seattle, Washington 98104
206.381.3300 • F: 206.381.3301

ground. Non-limiting examples of the user interface 52 are a keyboard, a mouse, or other input device for allowing a user to interact with the processor 46. The sensor 44 generates an image frame array (i.e., image or sensor information) and sends the image frame array to the processor 46 for correction. The processor 46 adjusts the received digital image frame array

- 4 -

ground. Non-limiting examples of the user interface 52 are a keyboard, a mouse, or other input device for allowing a user to interact with the processor 46. The sensor 44 generates an image frame array (i.e., image or sensor information) and sends the image frame array to the processor 46 for correction. The processor 46 adjusts the received digital image frame array

5   to compensate for previously-determined noise of the sensor 44 and light scattering effects of the optical element 54. The processor 46 then generates an image based on the corrected image frame array and sends the generated image to the display 50 for presentation. It will be appreciated that the components shown in FIGURE 1 can be included within a single device or may be remotely located from one another over a network and in separate devices. It will

10   be appreciated that the components of the system 40 are common off-the-shelf components and an explanation of these components is not necessary for understanding of the present invention.

Referring now to FIGURE 2, an exemplary process 100 is performed by the processor 46 (FIGURE 1). At a block 110, characteristics of a sensor 44 are determined and

15   images generated by the sensor 44 are enhanced according to the determined characteristics. The determination of sensor characteristics and adjustment of the image frames produced by the sensor 44 are described in more detail below in FIGURE 3. At a block 118, light scattering effects are removed from the enhanced image frame. The removal of light scattering effects is illustrated in more detail below in FIGURE 8. At a block 120, the image

20   frame is normalized. Normalization is described in more detail below in FIGURE 6. At a block 122, the processor 46 generates an image based on the normalized image frame with the removed light scattering effects and sends the generated image to the display 50 for presentation or to the memory 48 for storage.

Referring now to FIGURE 3, an exemplary process 150 determines characteristics of

25   the sensor 44 and enhances image frames based on the determined sensor characteristics from the block 110 (FIGURE 2). Image frames generated by the sensor 44 are produced at a predefined interval and are sized based on the array of sensing elements of the sensor 44. The array of sensing elements produces an array of frame unit data (hereinafter frame unit). The array of frame unit data is an image frame. Each frame unit includes a radiation value (i.e.,

30   radiance). At a block 154, a stable region of interest is selected from a mask region of an array of sensing elements of the sensor 44. Selection of the stable region of interest is shown in more detail below in FIGURE 4. At a block 156, the image frames used in normalization at the block 120 (FIGURE 2) are enhanced using information from the selected stable region of interest. The block 156 includes a block 158 that generates and enhances a set of image

35   frames produced by the sensor 44 being exposed to a known light quantity. The frames

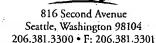ground. Non-limiting examples of the user interface 52 are a keyboard, a mouse, or other input device for allowing a user to interact with the processor 46. The sensor 44 generates an image frame array (i.e., image or sensor information) and sends the image frame array to the processor 46 for correction. The processor 46 adjusts the received digital image frame array

- 4 -

- 4 -

25315
PATENT TRADEMARK OFFICE

BOEI-1-1182AP.doc

BLACK LOWE & GRAHAM PLLC

816 Second Avenue
Seattle, Washington 98104
206.381.3300 • F: 206.381.3301

exposed to light are created by having the sensor face a calibration device called an integrating sphere, which produces a uniform light source of know intensity. At a block 160, a set of image frames produced by the sensor 44 being exposed to dark are generated and enhanced. Exposing the sensor 44 to dark includes placing a lens cover over the sensor 44. At

5   a block 162, an image frame generated by the sensor 44 is enhanced. The enhancement that is performed at the blocks 158, 160, and 162 is shown in more detail in FIGURE 5. The results of the process 150 (FIGURE 3) are enhanced image frames, which include an enhanced desired image frame, enhanced dark exposed frames, and enhanced frames exposed to the known light quantity. Exposing the sensor 44 to light and dark and enhancing the light and

10   dark frames are suitably performed under test conditions possibly by the sensor manufacturer before product delivery or could be performed by a user before operation of the sensor 44.

Referring now to FIGURE 4, an exemplary process 200 selects a stable region of interest from the block 154 (FIGURE 3). At a block 206, using an image frame produced by the sensor 44 under a known dark condition (i.e., exposed to dark), a column of frame units

15   of the frame image is selected from a known mask area of the sensor 44. The known mask area is suitably an area near an edge of the sensor 44 where sensing elements are permanently masked or covered by a structure of the sensor 44. In one non-limiting example, the mask area suitably is around 20 frame unit columns wide and around 1,024 frame unit rows high. At a block 208, a standard deviation for the frame units in the selected columns is

20   determined. At a block 210, the rows in the selected column that exhibit a desirable standard deviation are selected. In one non-limiting example, the rows selected start at row 100 and end at row 900. At a decision block 212, the process 200 returns to the block 206 if it is determined that a predefined number of columns have not been selected. If at the decision block 212 a predefined number of columns have been selected, at a block 216 a mean and

25   standard deviation for the selected rows and columns are determined over a set number of frames. In one non-limiting example, the number of frames that are used is between 100 and 1000. At a block 218, columns exhibiting the desirable standard deviation over the set of frames are selected. The selections performed in the process 200 are suitably performed by a user analyzing the determined standard deviation information to determine the desirable rows

30   and columns to select. It will be appreciated that the selections performed in the process 200 may be performed automatically by an application program executed by the processor 46.

Referring now to FIGURE 5, an exemplary process 250 enhances received image frames as shown in the block 156 (FIGURE 3). At a block 252, for each image frame produced by the sensor 44, a mean and a standard deviation are determined for the frame

35   units within the selected region of interest in the masked area. At a block 254, a

25315
PATENT TRADEMARK OFFICE

BOEI-1-1182AP.doc

BLACK LOWE & GRAHAM PLLC

816 Second Avenue
Seattle, Washington 98104
206.381.3300 • F: 206.381.3301

determination is made for the frame units of a produced image frame within the masked area that are below a predefined threshold value. In one non-limiting example, the predefined threshold value suitably is around 6 times the determined standard deviation for the frame image added to the determined mean (mean + (6 x standard deviation)). At a block 256, the mean is determined only for the frame units below the threshold value. At a block 258, a mean difference value is determined based on the determined mean of each frame unit below the threshold value and a predefined offset coefficient. This is performed on each frame separately. This allows removal of time varying components from the image. The offset coefficient is applied to allow noise variations around the dark zero value. In one non-limiting example, the determined mean is subtracted from coefficient = 150 for determining the mean difference value. This coefficient is an electrical offset. The offset is used because there exists noise when the sensor is tested under the dark condition. It will be appreciated that other coefficient values may be used. At a block 260, the determined mean difference value is added to each frame unit in the frame image. The process 250 repeats for every frame image. The results of the block 260 are returned to the respective blocks 158, 160, and 162 within the enhanced block 156 (FIGURE 3).

FIGURE 6 illustrates normalization from the block 120 (FIGURE 2). At a block 280, a mean is calculated for each frame unit across all of the enhanced image frames associated with the dark condition. The result of the block 280 is identified as B. At a block 282, the mean is calculated for each frame unit of the enhanced image frames exposed to the known light condition. The output of the block 282 is identified as A. The calculated mean B for each frame unit is subtracted from the corresponding frame unit in the enhanced image frame (i.e. array of frame units of the image frame) C at a function 284. The calculated mean B for each frame unit is subtracted from the corresponding frame unit in the calculated mean A at a function 286, thereby removing the mean dark values from the image frames. At a function 288, the enhanced image C - B is divided by the mean image frame based on the known light condition as follows: C - B/A - B. At a block 290, an average value for the frame units in a predefined center area of the frame image A - B is calculated. The calculated average value is identified as E. At a function 289, the result of the function 288 is multiplied by the calculated average E and then added to a coefficient. A non-limiting example of the coefficient that is added is 150. Thus, the results of normalization are as follows:

$$(C - B/A - B) \times E + 150$$

FIGURE 7 illustrates an image frame A − B, and an area 298 identifies the frame units that are used for the calculation of the average done in the block 290 (FIGURE 6). In one non-limiting example, the area 298 is 16 frame units by 16 frame units.

- 6 -

In one embodiment, the original raw data included within the selected region of interest from the received image frame (block 110) is reinserted back into the normalized image frame.

Referring now to FIGURE 8, an exemplary process 300 adjusts light scattering effects resulting from an optical element 54, such as without limitation an electronic shutter, within the sensor 44. The process 300 is performed at the block 118 (FIGURE 2). At a block 310, the average values of the frame units within the previously-determined region of interest of the enhanced image frame are calculated. At a block 312, the calculated average for all of the frame units is subtracted from each of the frame units in the enhanced image frame. The image frame result of the subtraction at the block 312 is considered band data. At a block 314, the band data is separated into subarrays of a predefined area and the centers for each of the subarray are determined. At a block 318, all the frame units for each subarray are totaled thereby generating a total S_s for each subarray. At a block 320, the distance of a frame unit from the center of a subarray is determined. At a block 322, a previously calculated effects value is retrieved from an effects table. The effects table includes light scattering values that indicate each frame unit's effect on each frame unit, which have been determined by measurement of camera characteristics. A frame unit's effect on other frame units is based on light scattering properties of the optical element 54. At a block 326, the retrieved effects value is multiplied by the associated subarray total S_s, thereby generating an effects value S_{eff}. At a decision block 328, the process 300 returns to the block 320 if it is determined that not all of the subarrays have been analyzed for a frame unit. If all the subarrays for a frame unit have been analyzed, at a block 330 all the effects values S_{eff} are totaled for a particular frame unit. At a block 332, the sum of the S_{eff} values is subtracted from the same frame unit. At a decision block 340, if it is determined that not all of the frame units have been analyzed with respect to all of the subarrays, at a block 344 the process 300 moves to the next frame unit and returns to the block 320 to repeat until all of the frame units have been analyzed. If it is determined that all the frame units have been analyzed, the process 300 is complete.

FIGURE 9 illustrates some of the processing of the process 300 (FIGURE 8) applied to an enhanced image frame 450. Distances from a first frame unit 460 to centers of each subarray 462 are determined. The determined distance value is suitably compared to distances stored in a look-up table that is stored in the memory 48. The look-up table includes all possible distances between frame units 460 and a corresponding light scattering effects value. A retrieved light scattering effects value is multiplied by the sum of all frame units within the respective subarray. The product produces a relative light scattering effect of

- 7 -

the subarray on the frame unit 460. The products for all of the subarrays are added together and then subtracted from the frame unit 460, thereby canceling out the light scattering effects of all the subarrays upon the frame unit 460. It will be appreciated that other methods of canceling out the light scattering effects of frame units upon other frame units can be used.

5   For example, the process 300 described above can be performed for determining the direct light scattering effect of every frame unit upon each frame unit.

The S_s and scattering effects are fractional numbers requiring floating point numbers.

The process for removing light scattering effects may be performed on the enhanced image frames that were exposed to light.

10   It will be appreciated that a frame image may be corrected in real-time if enough processing power is provided. Thus, with real-time image generation streaming images (video) are possible.

While the preferred embodiment of the invention has been illustrated and described, as noted above, many changes can be made without departing from the spirit and scope of the

15   invention. For example, the steps of the processes described above may be performed in a different order and still accomplish the same or similar final results. Accordingly, the scope of the invention is not limited by the disclosure of the preferred embodiment. Instead, the invention should be determined entirely by reference to the claims that follow.